Search of Dark Matter pair production in ATLAS

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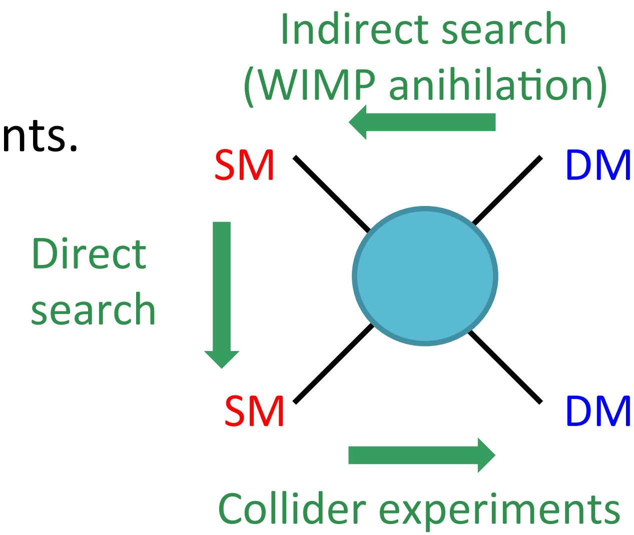
Dark matter search with mono-X events

- If Dark Matter couples to Standard Model (SM) particles, DM is searchable at collider experiments.
  - Weakly interacting massive particles (WIMPs), χ.
  - WIMP pair production at collider.

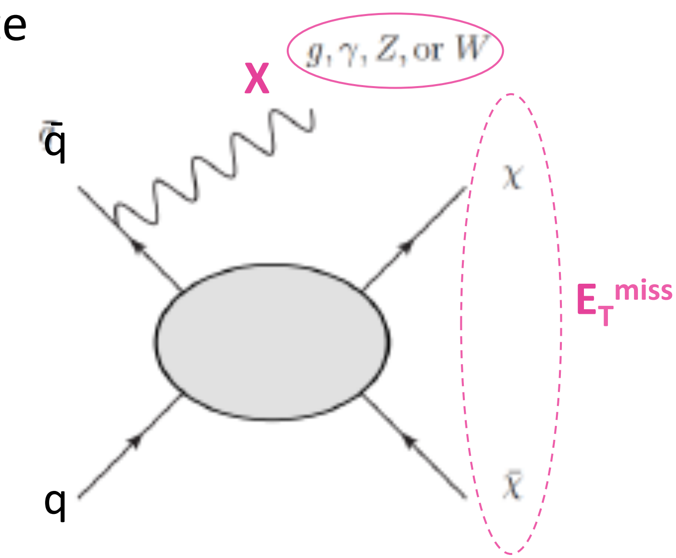


- Tag the pair-production system by the initial state radiation (ISR) of SM particles, X:

  $pp \to \chi\chi + X$

  - WIMPs don't interact with the detectors.
    → Large missing transverse energy, E_T^{miss}

➔Search of **Mono-X +** $\mathbf{E_T^{miss}}$



Mono-X interpretations

- Effective Field Theories (EFTs)
  - Contact interaction between SM particles and DM, χ.
  - Mediator is too heavy to be directly produced and is integrated out.
  - Two parameters:
    - Suppression scale: $\mathbf{M_*} = M_{med}/\sqrt{(g_{SM} g_{DM})}$
    - Dark matter mass: $\mathbf{m_\chi}$

M_{med}: mediator mass
g : coupling

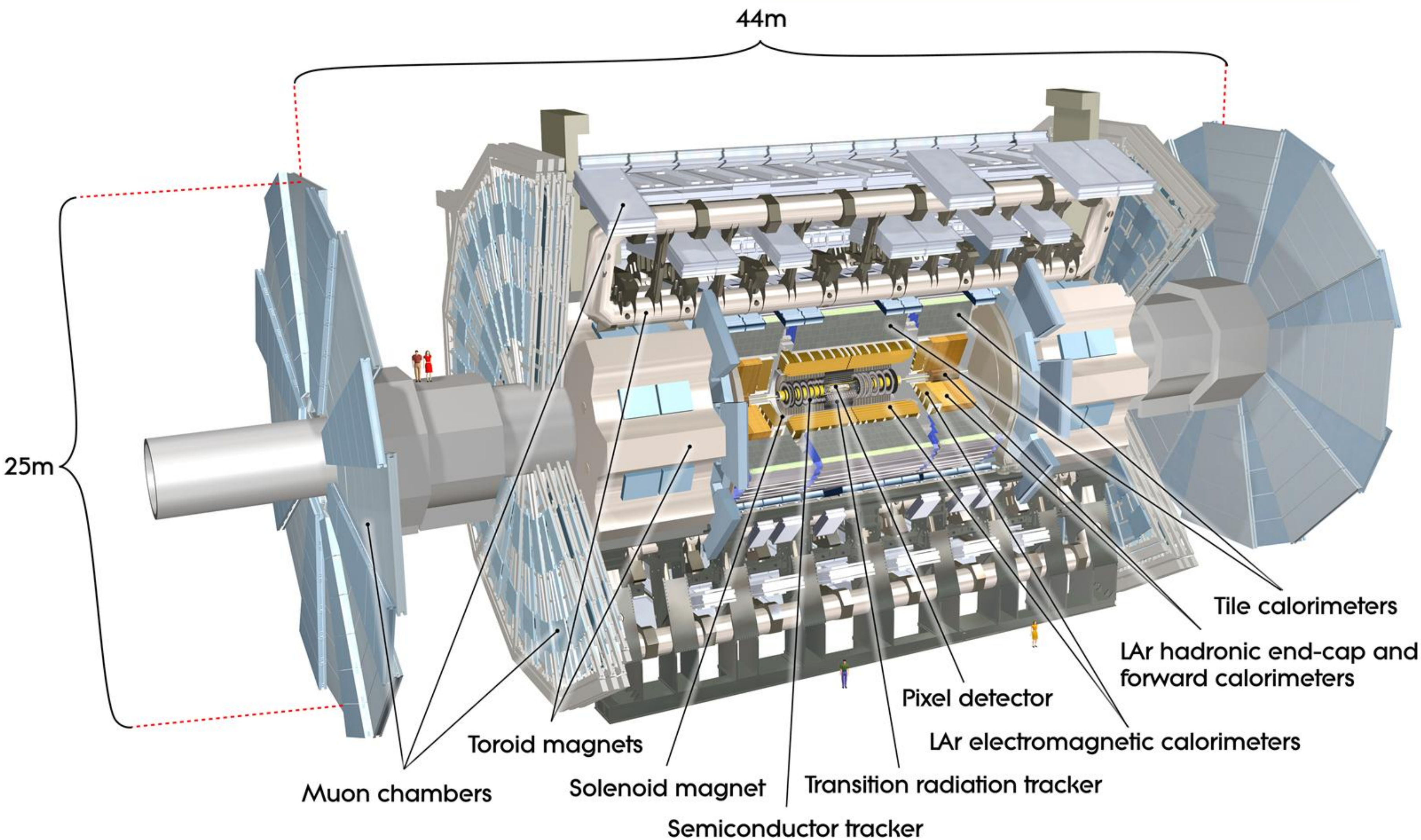
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Spin-dependent interaction (D8, D9)

- Simplified models
  - Mediator is not integrated out.
  - Addressing validity question of EFT at high energies.

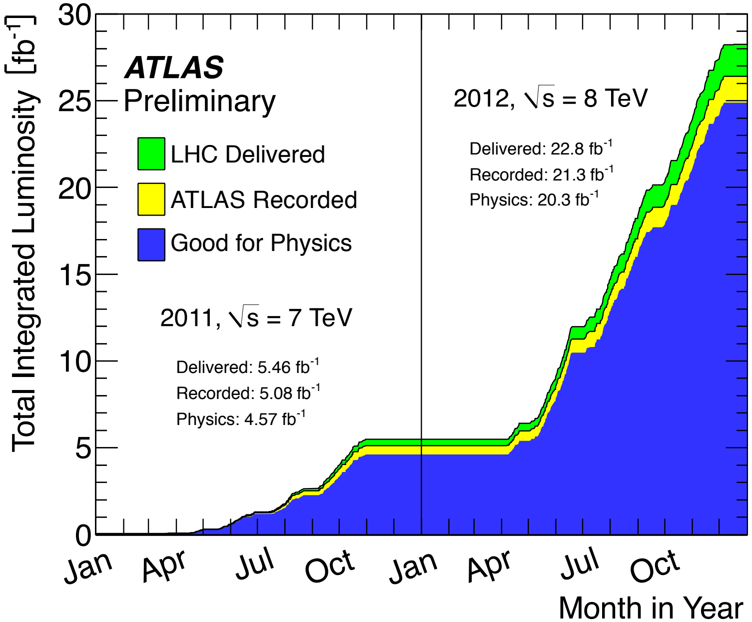
ATLAS detector

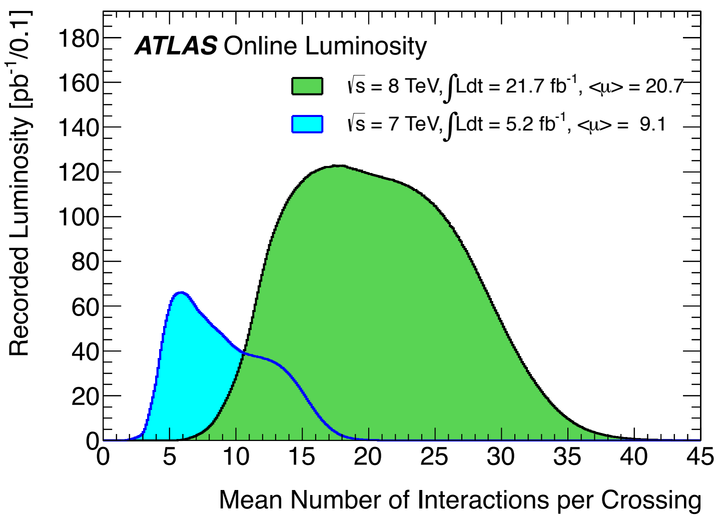
- Tracking system : $|\eta|<2.5$
- Calorimeter : $|\eta|<4.9$
- Muon system : $|\eta|<2.7$
- Three-level trigger system



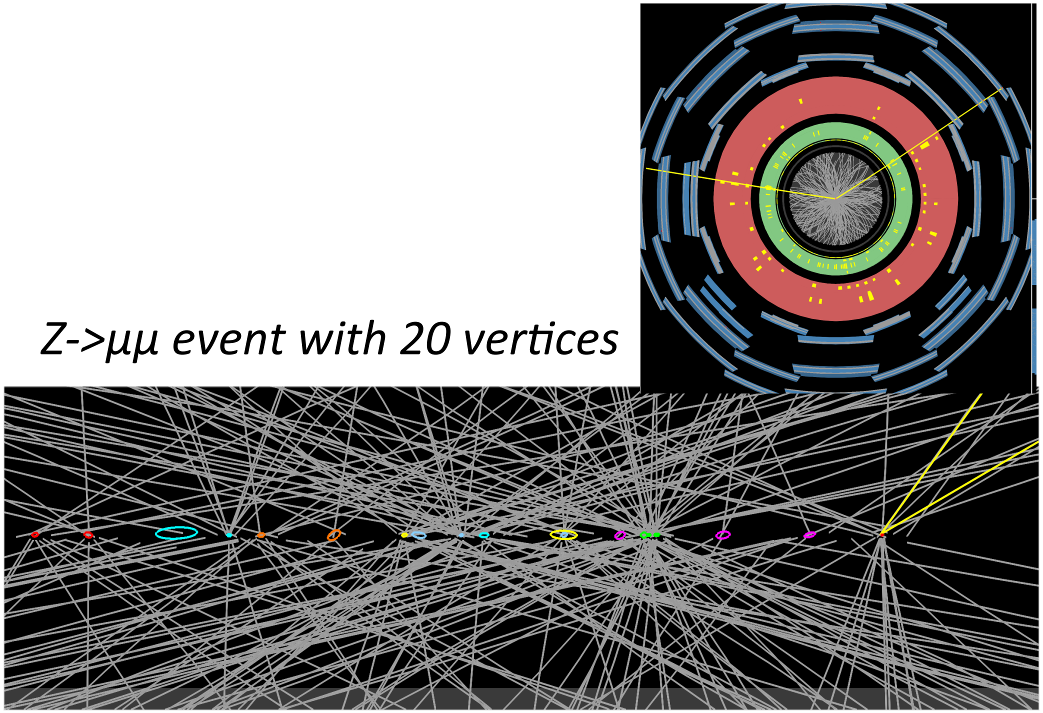
ATLAS data

- Available *pp* collision data
  - $\sqrt{s}$ = 7 TeV: 5 fb^{-1}
  - $\sqrt{s}$ = 8 TeV: 20 fb^{-1}
- Multiple interactions occurs simultaneously in a colliding.
  - Increased in 2012

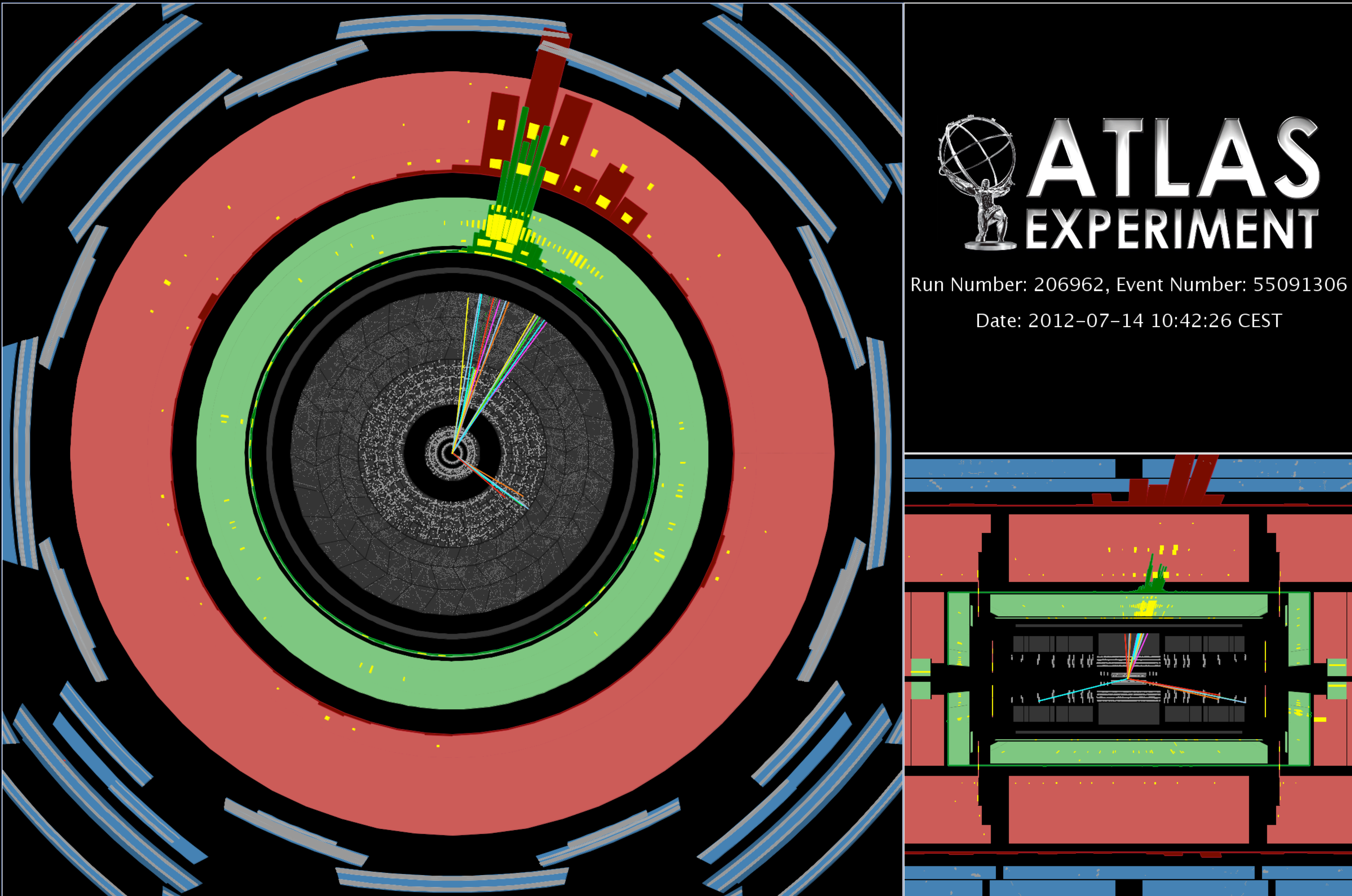




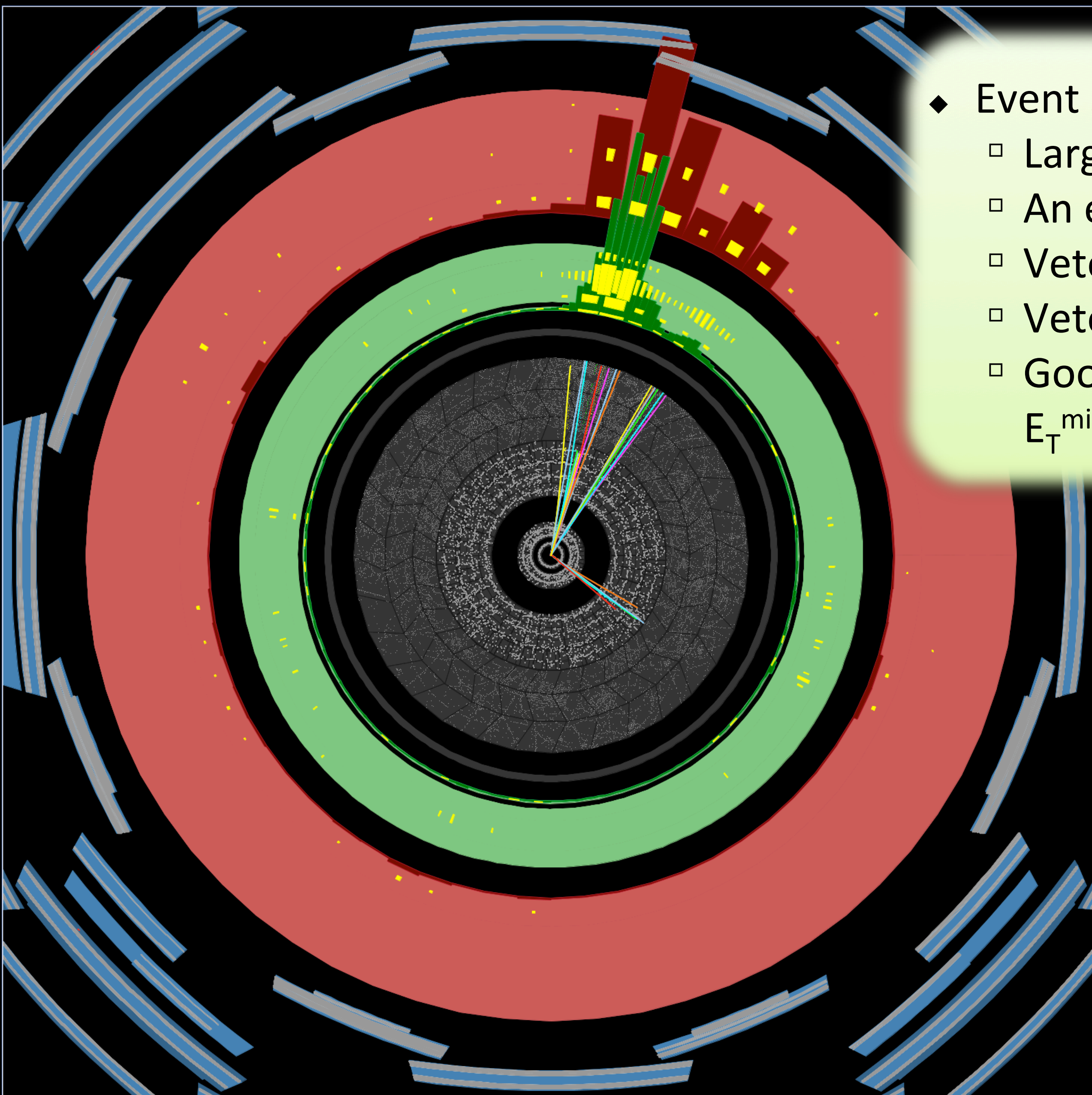
Z->μμ event with 20 vertices



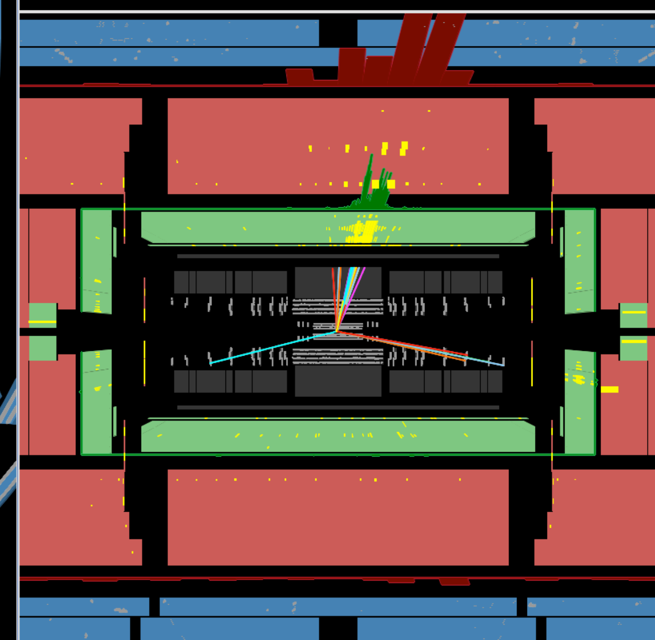
Mono-jet event at √s=8 TeV



Mono-jet event at √s=8 TeV



- Event selections
  - Large E_T^{miss}
  - An energetic object (X)
  - Veto on (extra) leptons
  - Veto on >1 additional jets
  - Good separation in ϕ between E_T^{miss}, X and additional jets



General analysis strategies

- Event selections
  - Large E_T^{miss}
  - An energetic object (X)
  - Veto on (extra) leptons
  - Veto on >1 additional jets
  - Good separation in ϕ between E_T^{miss}, X and additional jets

- SM processes are background to the DM search.
  - W/Z backgrounds
    - e.g: Z->νν or W->lν with lepton outside of the acceptance, etc
    - Usually estimated using control regions with lepton requirements.
  - Multijet backgrounds
    - Estimated by events with jet aligned with the E_T^{miss} direction.
  - Diboson production, Top production
    - Usually estimated based on MC simulation.

- **Mono-γ search**
- Mono-jet search
- Mono-W/Z (hadronic) search
- Mono-W search
- Mono-Z search

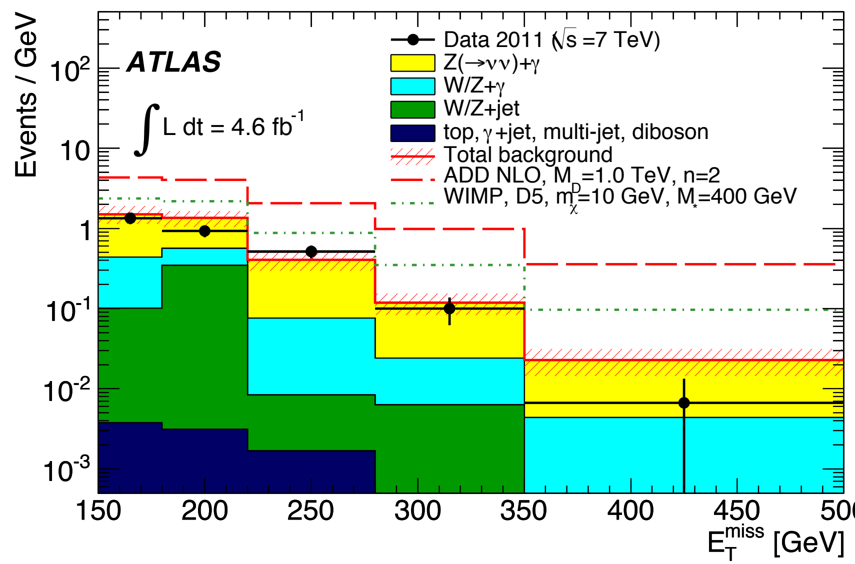
$\sqrt{s}$=7 TeV, 4.6 fb^{-1}

PRL 110, 011802 (2013)

Mono-γ search analysis

- Event selection
  - Isolated, well-defined photon with $p_T^{\gamma} > 150$ GeV
  - $E_T^{miss} > 150$ GeV
  - Lepton veto
  - $N_{jet} < 2$ for $p_T^{jet} > 30$ GeV
  - $|\Delta\phi(\gamma, E_T^{miss})| > 0.4$, $|\Delta\phi(\gamma, jet)| > 0.4$, $|\Delta\phi(E_T^{miss}, jet)| > 0.4$
- Backgrounds
  - W/Z + γ ← control region
  - W/Z + jet ← estimation of fake γ from e or jet
  - γ + jet, multijet ← data

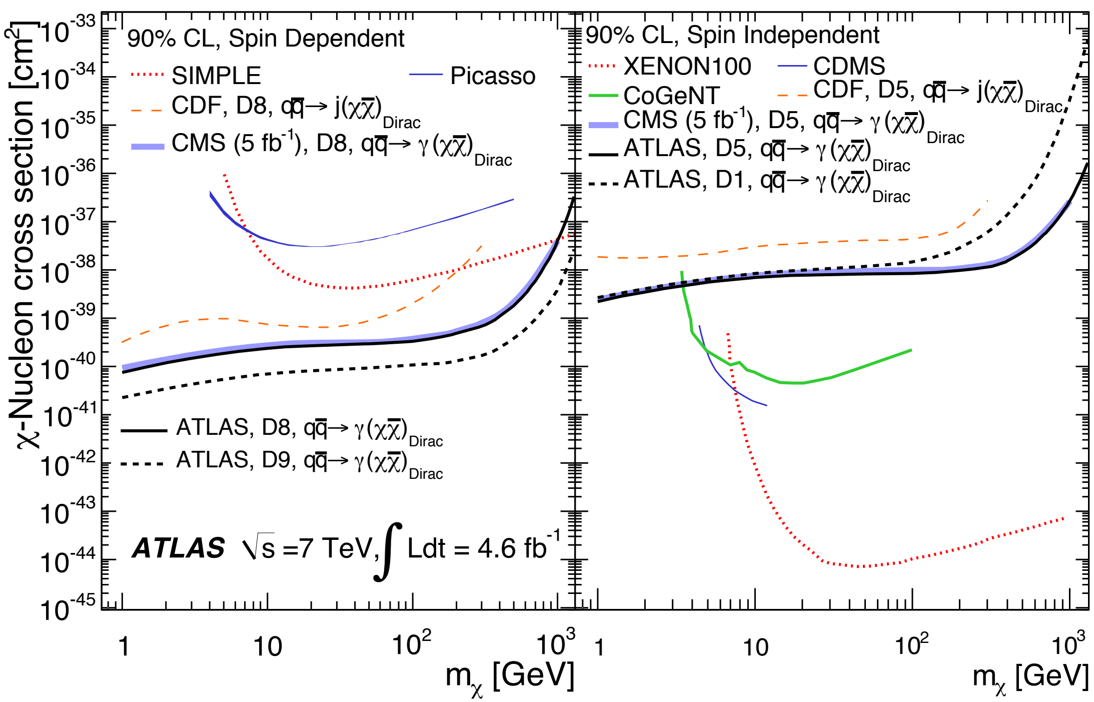
Background source	Prediction	±(stat)	±(syst)
$Z(\to \nu\bar{\nu}) + \gamma$	93	±16	±8
$Z/\gamma^*(\to \ell^+\ell^-) + \gamma$	0.4	±0.2	±0.1
$W(\to \ell\nu) + \gamma$	24	±5	±2
W/Z + jets	18	···	±6 (total)
Top	0.07	±0.07	±0.01
WW, WZ, ZZ, $\gamma\gamma$	0.3	±0.1	±0.1
γ + jets and multijet	1.0	···	±0.5 (total)
Total background	137	±18	±9
Events in data (4.6 fb^{-1})	116		



Mono-γ search results

- EFT operators D1, D5, D8 and D9 are considered.
- Limits set on M_*, for a given m_χ.
  → Converted to χ-nucleon cross-section limit for a comparison.

	m_χ = 1 GeV	m_χ = 1.3 TeV
D1	$M_* > 31$ GeV	$M_* > 5$ GeV
D5	$M_* > 585$ GeV	$M_* > 156$ GeV
D8	$M_* > 585$ GeV	$M_* > 100$ GeV
D9	$M_* > 794$ GeV	$M_* > 188$ GeV



- Limits from collider experiment is competitive at low m_χ.
- Spin-dependent limits are smaller than the direct searches.

- Mono-γ search
- **Mono-jet search**
- Mono-W/Z (hadronic) search
- Mono-W search
- Mono-Z search

Event selection (7TeV analysis)

$\sqrt{s}$=7 TeV, 4.6 fb^{-1}
JHEP04 (2013) 075

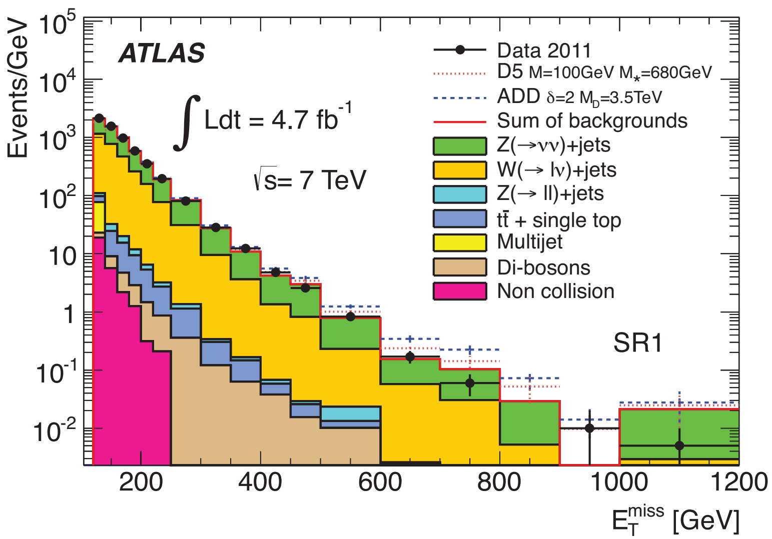
- Event selection
  - 4 Signal Regions (SR)
    - E_T^{miss}, $p_T^{jet,leading}$ > 120, 220, 350 and 500 GeV
      - anti-k_t jet with R=0.4, $|\eta|<2$
  - No more than one additional jet with p_T>30 GeV, $|\eta|<4.5$
    - $|\Delta\phi(\mathbf{p}_T^{miss}, \mathbf{p}_T^{jet\ 2})|>0.5$
  - Lepton vetos (loose definition for SR-leptons)
    - Electron: p_T>20 GeV, $|\eta|<2.47$, Muon: p_T>7 GeV, $|\eta|<2.5$
- Dominant background
  - Z/W + jets ← Estimated using Control Region (CR)
    - CR is defined with explicit (tight) lepton requirement

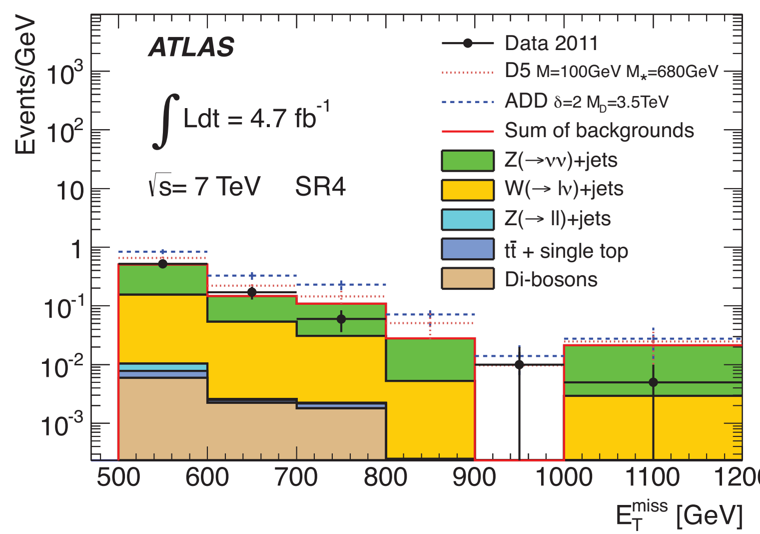
SR process	$Z \to \nu\bar{\nu}$+jets	$W \to \tau\nu$+jets $W \to \mu\nu$+jets	$W \to e\nu$+jets	$Z \to \tau^+\tau^-$+jets $Z \to \mu^+\mu^-$+jets
CR process	$W \to e\nu$+jets $W \to \mu\nu$+jets $Z \to e^+e^-$+jets $Z \to \mu^+\mu^-$+jets	$W \to \mu\nu$+jets	$W \to e\nu$+jets	$Z \to \mu^+\mu^-$+jets

Results

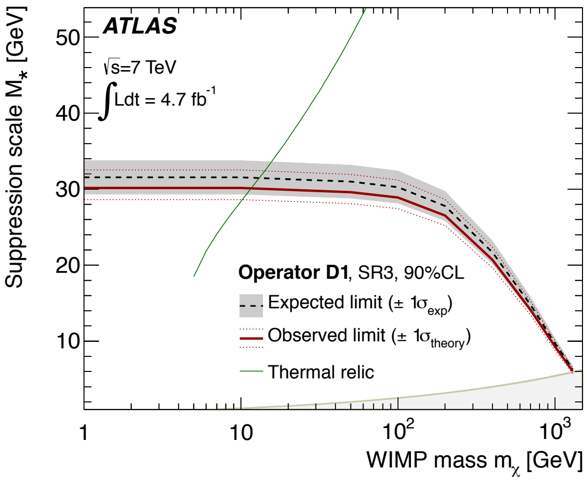
- Dominant systematic uncertainties from:
  - JES, E_T^{miss}
  - Theoretical uncertainties of W and Z production, shapes of W
- Good agreement with the SM predictions

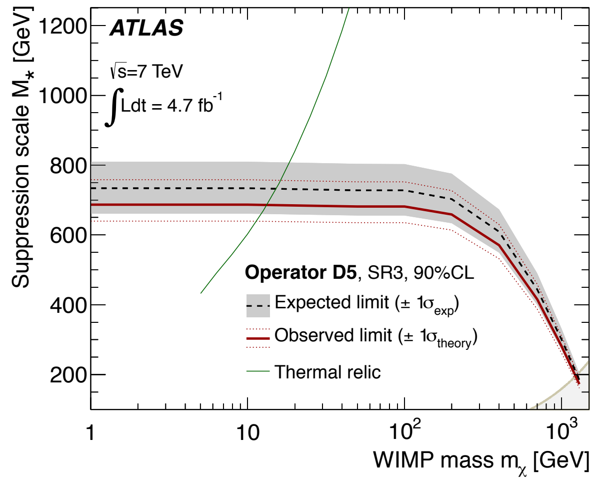
	SR1	SR2	SR3	SR4
$Z \to \nu\bar{\nu}$+jets	63000 ± 2100	5300 ± 280	500 ± 40	58 ± 9
$W \to \tau\nu$+jets	31400 ± 1000	1853 ± 81	133 ± 13	13 ± 3
$W \to e\nu$+jets	14600 ± 500	679 ± 43	40 ± 8	5 ± 2
$W \to \mu\nu$+jets	11100 ± 600	704 ± 60	55 ± 6	6 ± 1
$t\bar{t}$ + single t	1240 ± 250	57 ± 12	4 ± 1	—
Multijets	1100 ± 900	64 ± 64	8^{+9}_{-8}	—
Non-coll. Background	575 ± 83	25 ± 13	—	—
$Z/\gamma^* \to \tau\tau$+jets	421 ± 25	15 ± 2	2 ± 1	—
Di-bosons	302 ± 61	29 ± 5	5 ± 1	1 ± 1
$Z/\gamma^* \to \mu\mu$+jets	204 ± 19	8 ± 4	—	—
Total Background	124000 ± 4000	8800 ± 400	750 ± 60	83 ± 14
Events in Data (4.7 fb^{-1})	124703	8631	785	77

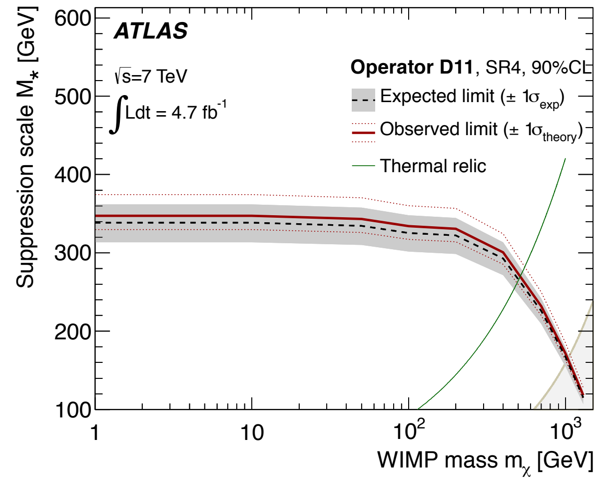


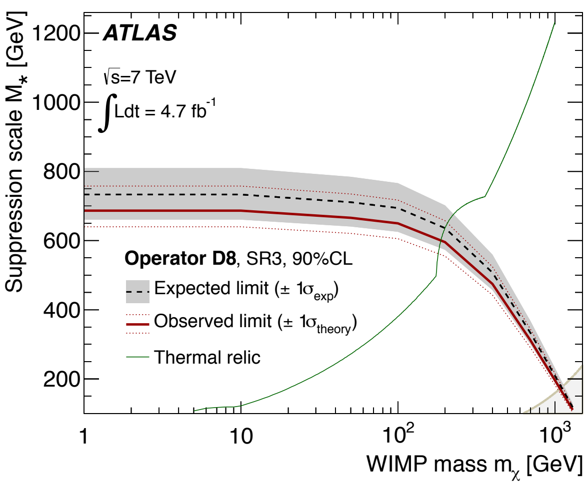


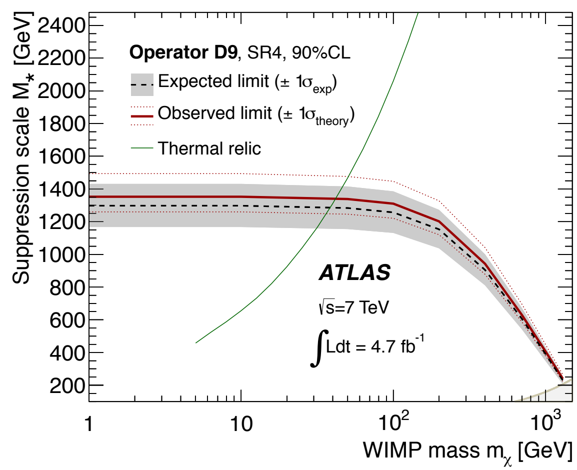
EFT interpretation







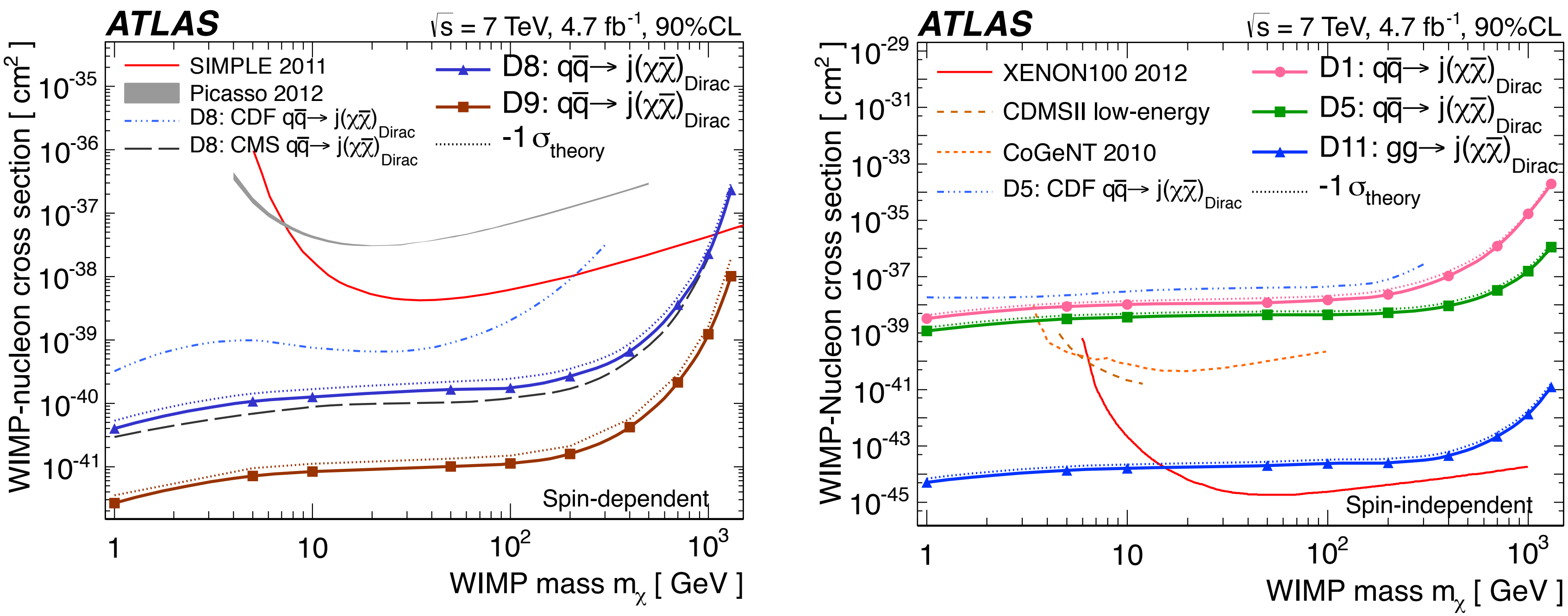




- M_*: suppression scale

  $M_* = M_{med} / \sqrt{(g_{SM} g_{DM})}$
- m_χ: WIMP mass

Cross-section limits



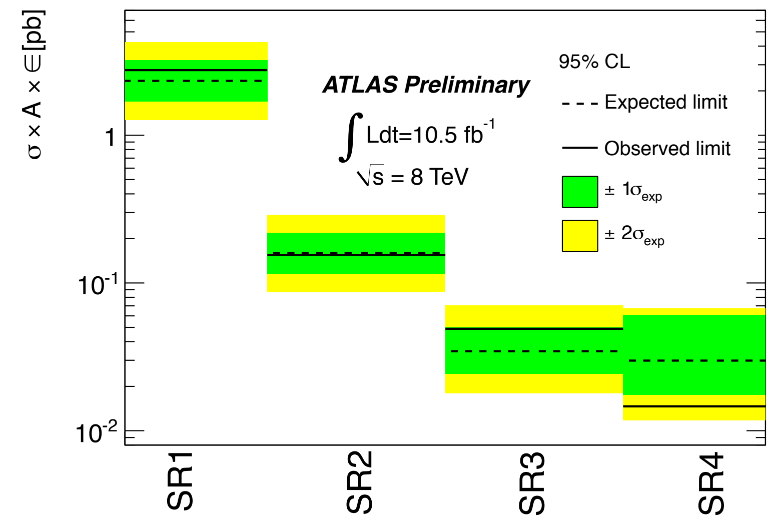
- Tighter constraint compared to Mono-γ search (D8, D9 and D5)

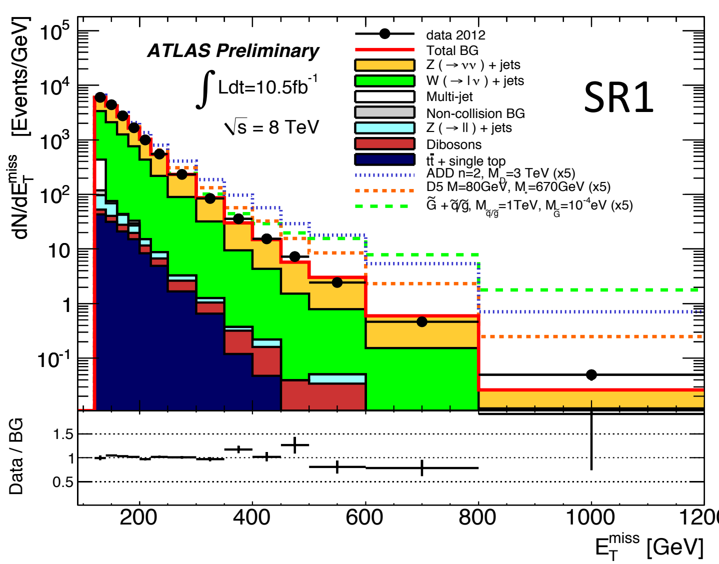
√s=8 TeV, 10.5 fb^{-1}

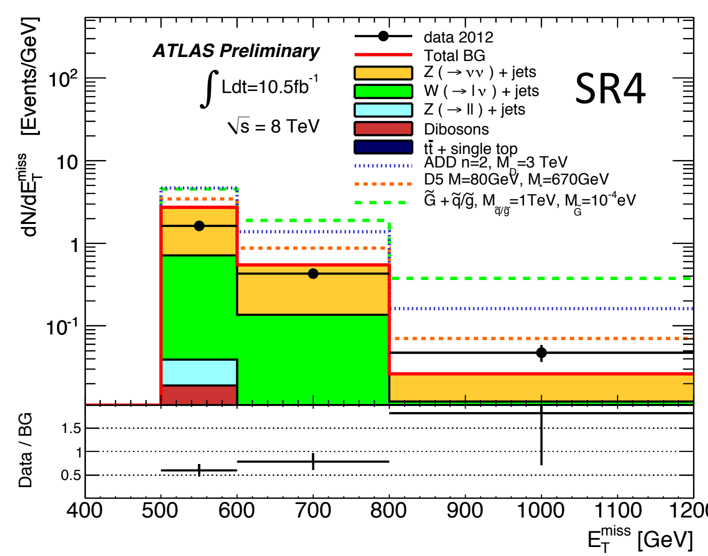
ATLAS-CONF-2012-147

8 TeV measurement

- 8 TeV data 10.5 fb^{-1}
  - Half of the full statistics.
- Analysis follows closely the 7 TeV measurement.
- No excess is seen.

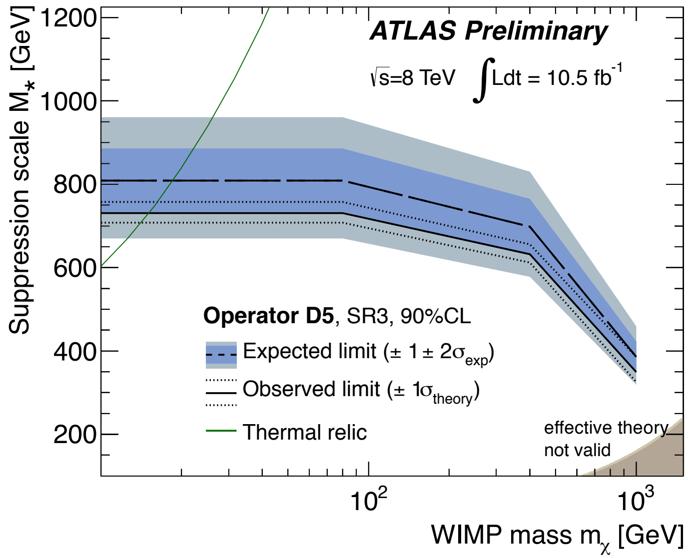


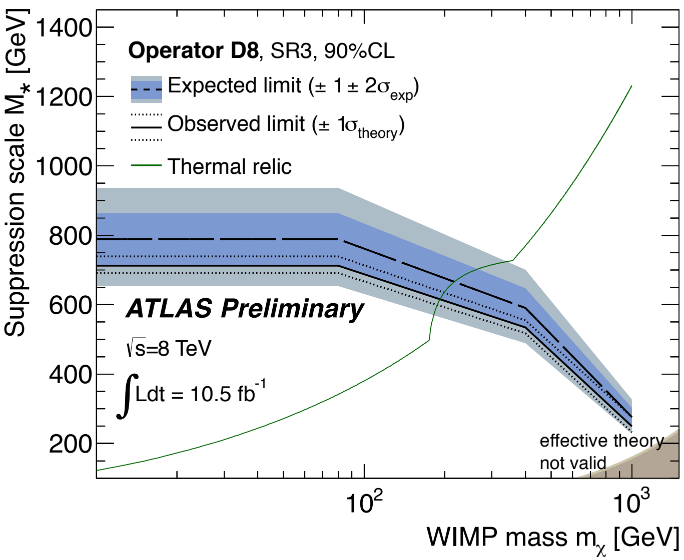


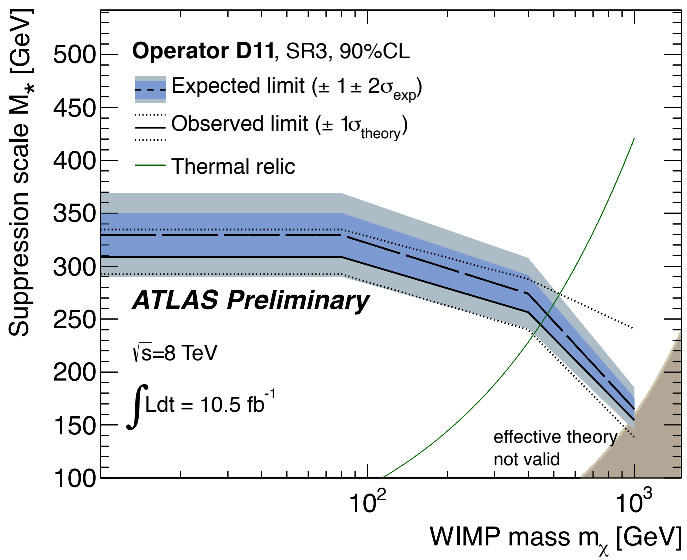


Results

- Expected lower limits for D5 and D8 is larger by 10% than 7 TeV.
- Expected lower limits for D11 is unchanged.



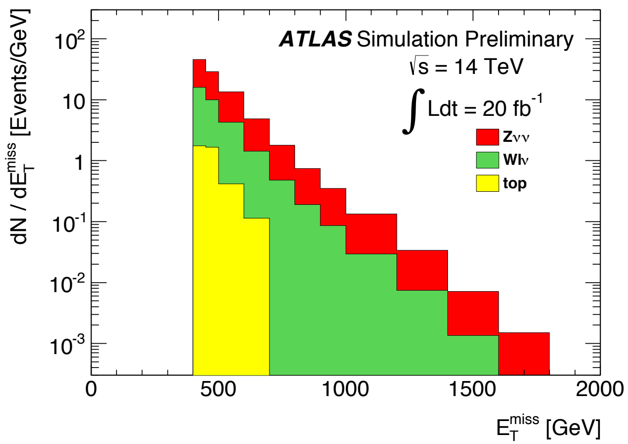




MC study of sensitivity at 14 TeV

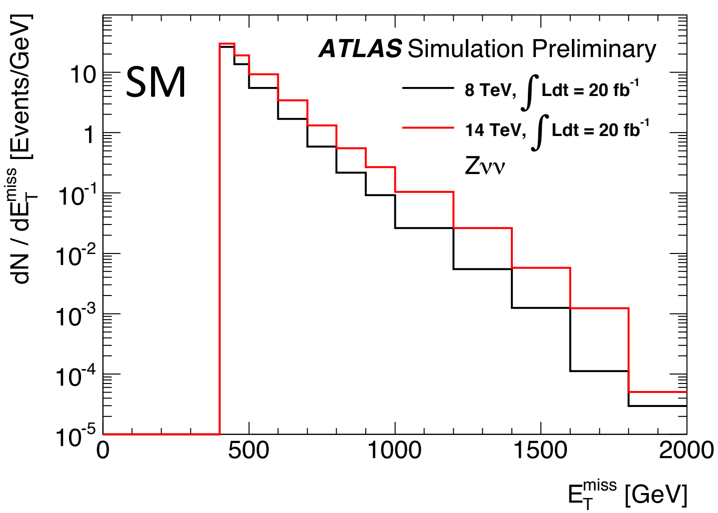
Simulation only
ATL-PHYS-PUB-2014-007

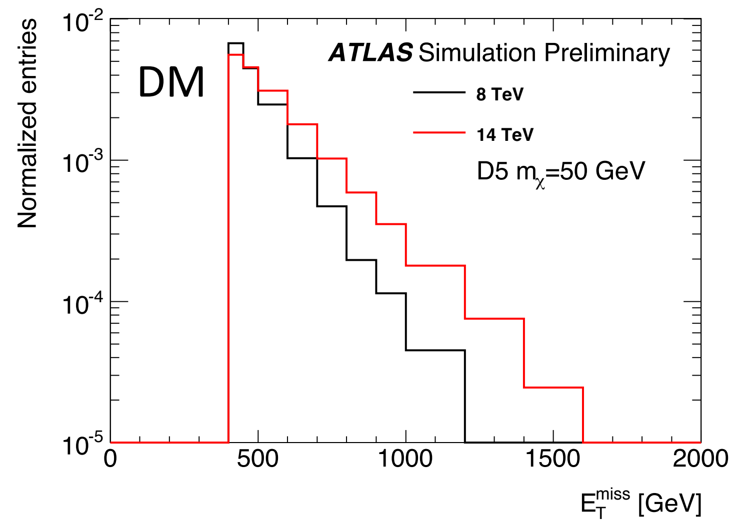
- Event selection



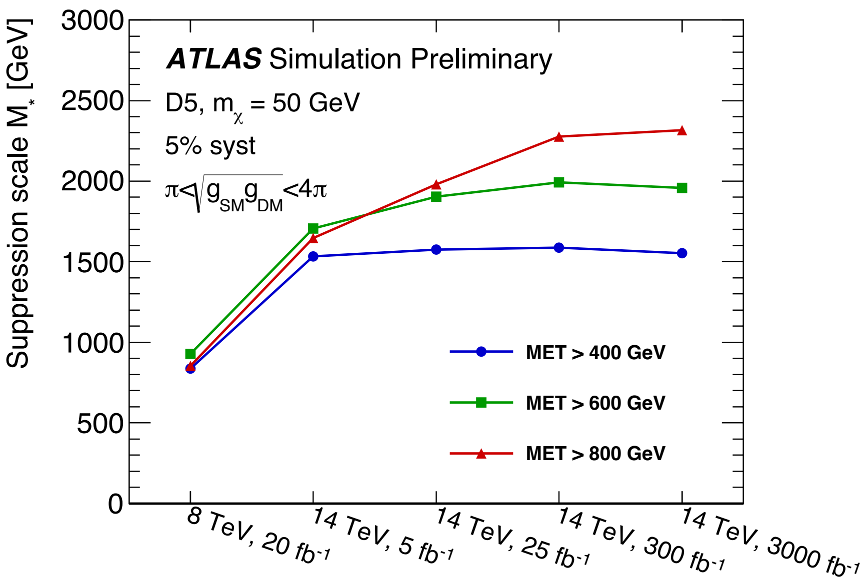
	$\sqrt{s}$ = 8 TeV	$\sqrt{s}$ = 14 TeV
Leading jet	p_T>300 GeV, $\lvert\eta\rvert$<2.0	
E_T^{miss}	E_T^{miss} > 400, 600, 800 GeV	
Jet definition	p_T>30 GeV, $\lvert\eta\rvert$<4.5	p_T>50 GeV, $\lvert\eta\rvert$<3.6
	N_{jet} <=2	
	$\lvert\Delta\phi(E_T^{miss}, jet)\rvert$ > 0.5	
Lepton veto	p_T>7 GeV, $\lvert\eta\rvert$<~2.5	

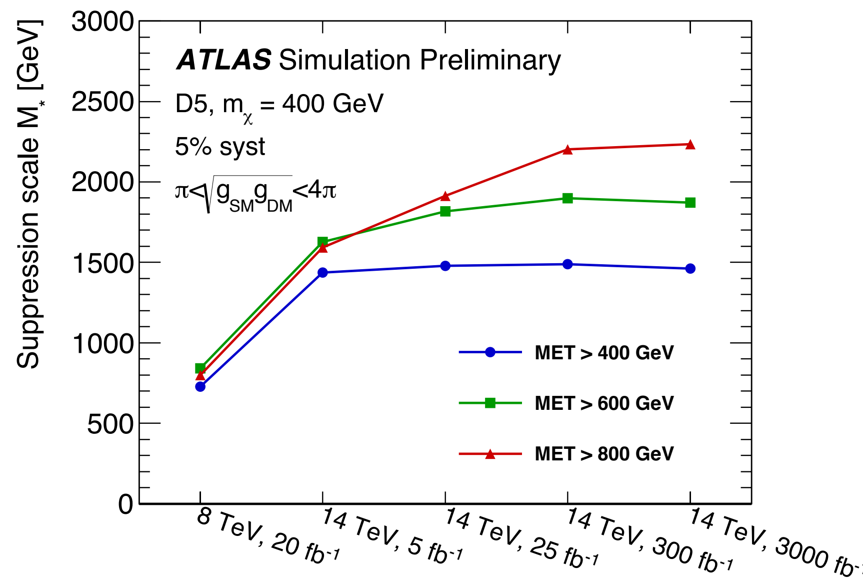
- Harder E_T^{miss} distributions expected at 14 TeV, more significant for signal.



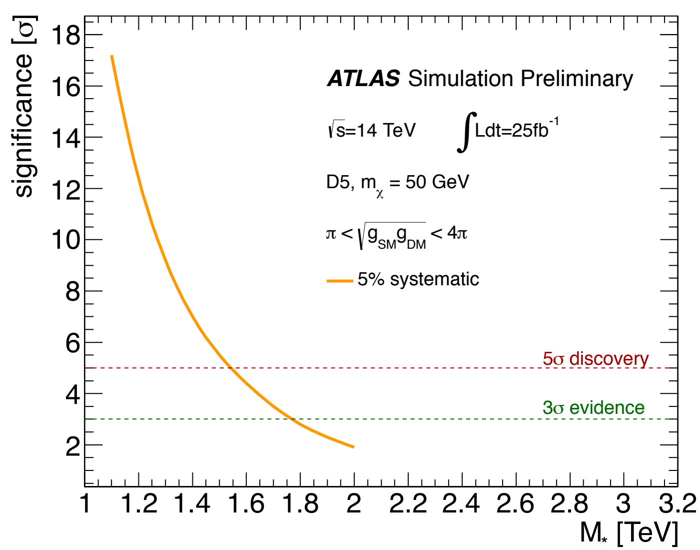


Prospects with EFT approach (D5)





- Limits are expected to be improved by a factor of 2, with the 14 TeV data expected in the 1st year.
- For m_χ = 50 GeV, M_* detection can be done up to 1.5 TeV at 5σ. (first year of data-taking.)



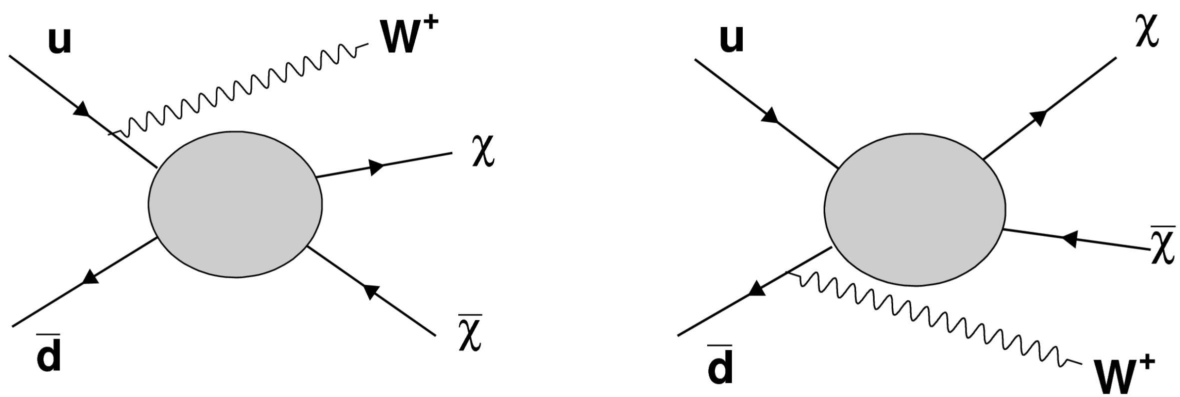
- **Mono-γ search**
- **Mono-jet search**
- **Mono-W/Z (hadronic) search**
- **Mono-W search**
- **Mono-Z search**

Mono-W/Z search

$\sqrt{s}$=8 TeV, 20 fb^{-1}
PRL 112 041802 (2014)

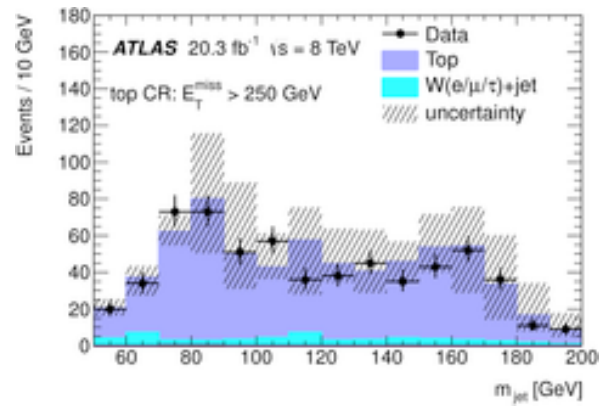
- Strong constraint from mono-jet, due to large radiation rate of q and g.
  - Assumption: same coupling for up-type and down-type quarks.
    C(u) = C(d)
- If DM has opposite coupling to up-type and down-type quarks
    C(u) = -C(d)

  ➔ Interference can make Mono-W production be a dominant process



Analysis

- Hadronic decay of W/Z → Reconstructed as **a massive fat-jet**
  - **Large-R (=fat) jet**: Cambrige-Aachen jet with R=1.2
    - m_{jet} is well described by simulation in top events.
  - Narrow-jet: anti-k_T jet with R=0.4

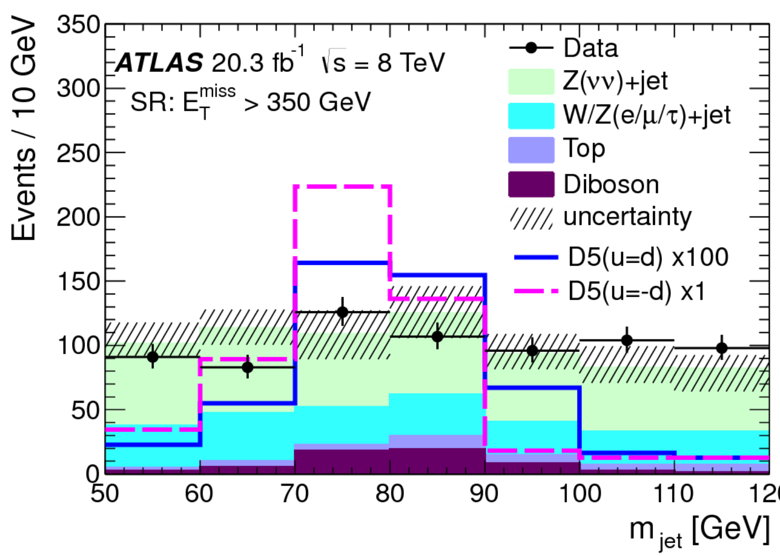


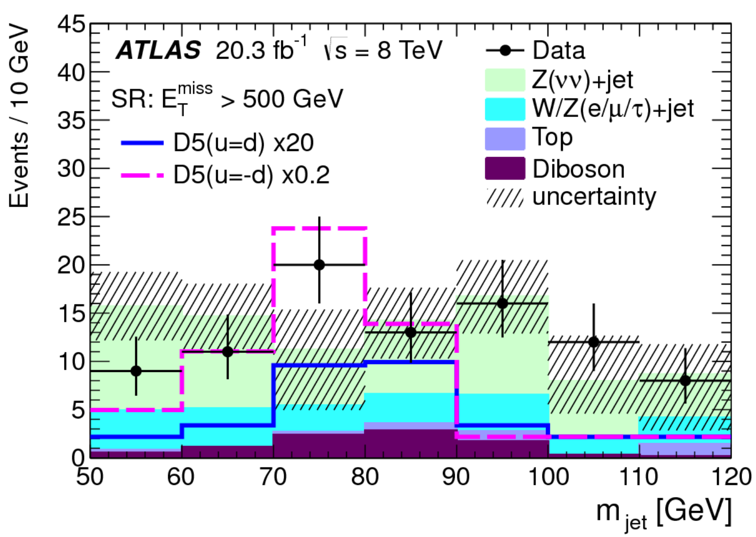
- Event selection
  - Large-R jet with p_T>250 GeV, |η|<1.2, 50<m_{jet}<120GeV
  - Veto on e, μ, γ
  - Veto on >1 narrow jet with p_T>40 GeV, |η|<4.5
    - Not overlapping with large-R jet
  - Veto if any narrow jet is close to E_T^{miss} as $|\Delta\phi(E_T^{miss}, \text{jet})| < 0.4$
  - E_T^{miss} requirements
    - 2 signal regions: E_T^{miss} > 350 GeV, 500 GeV

Event yields

Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu,\ Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
$WW,\ WZ,\ ZZ$	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

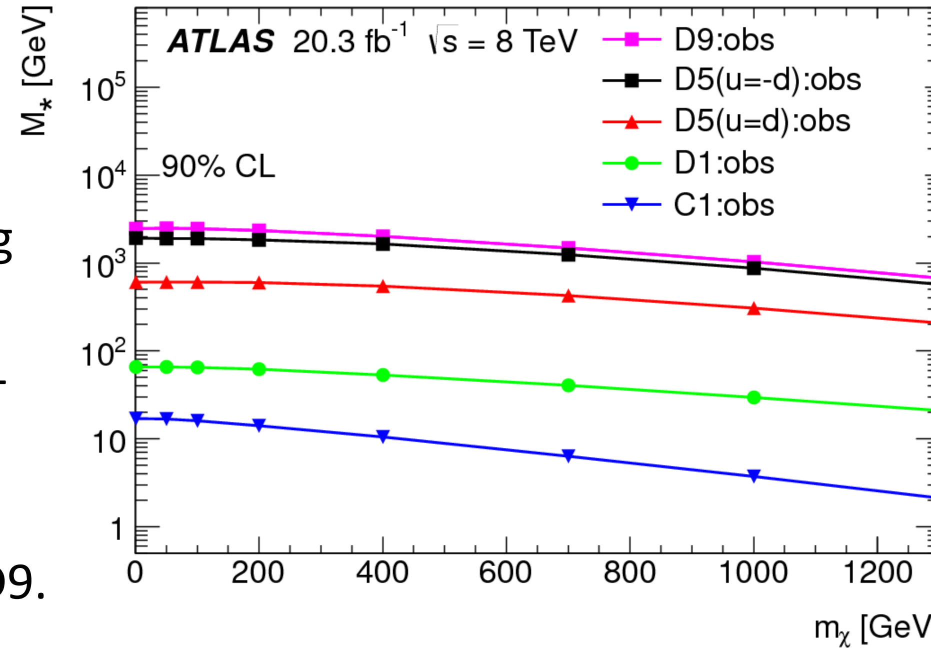
- W/Z backgrounds estimated using control regions.
- No excess is observed

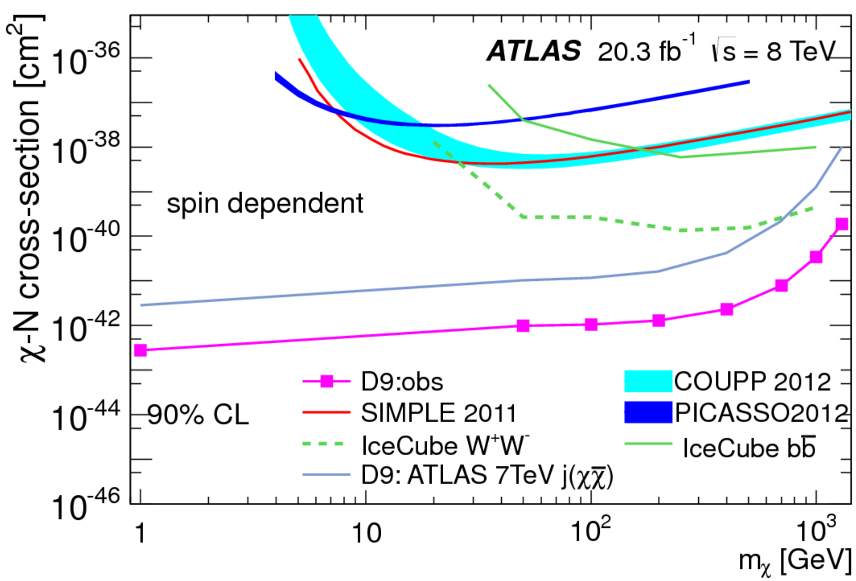


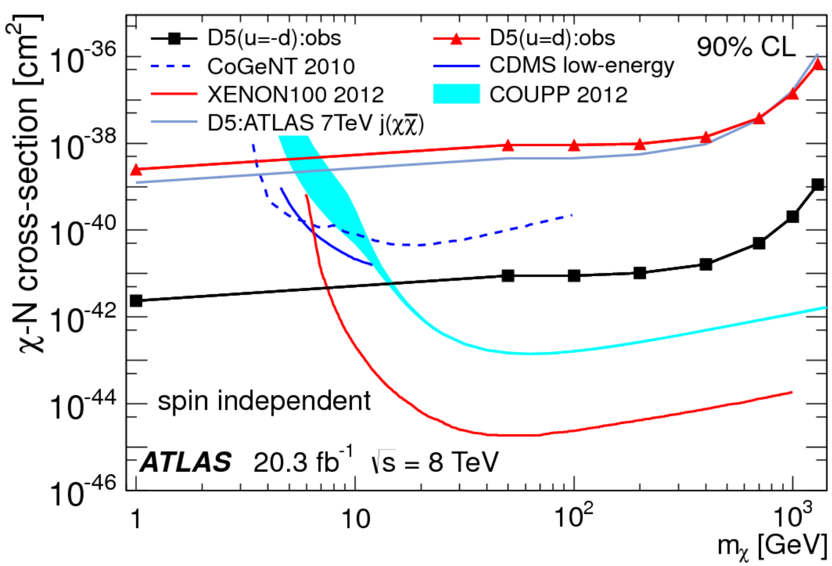


Results

- Senario with C(u) = -C(d) gives strong constraint.
- For D5 with C(u) = C(d), 7 TeV mono-jet result is slightly better.
- 8 TeV mono-W/Z gives more sensitivity than 7 TeV mono-jet for D9.







- Mono-γ search
- Mono-jet search
- Mono-W/Z (hadronic) search
- **Mono-W search**
- Mono-Z search

Search with one lepton + missing E_T

$\sqrt{s}$=8 TeV, 20 fb^{-1}
arXiv 1407.7494
accepted by JHEP

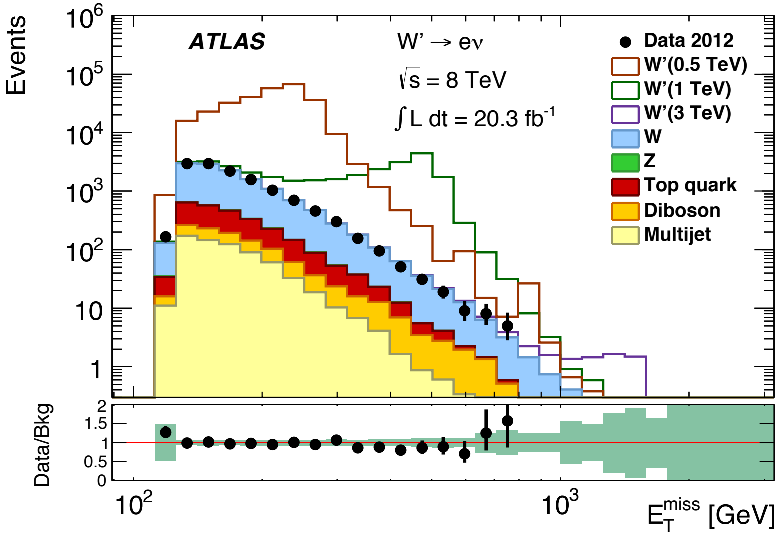
- Analysis is done for W' search, but can be interpreted as DM search as well.
- Event selection

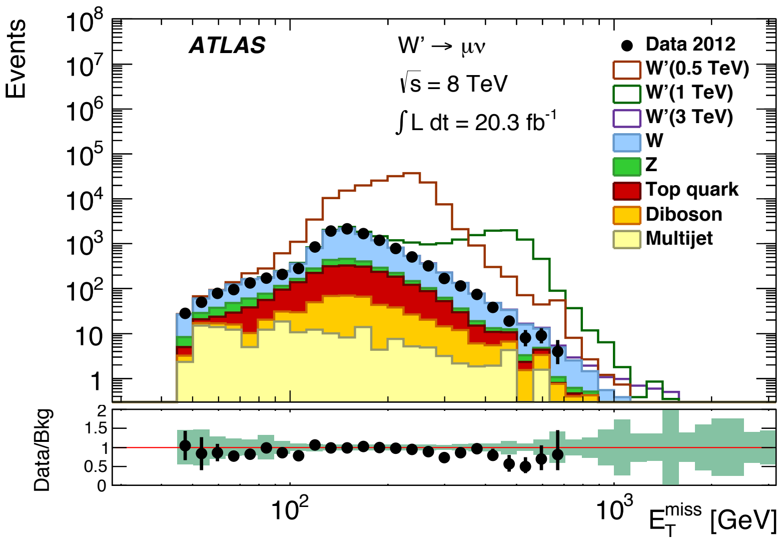
  e-channel:
  - Electron with E_T > 125 GeV
  - E_T^{miss} > 125 GeV
  - Veto on additional electron with E_T > 20 GeV

  μ-channel:
  - Muon with E_T > 45 GeV
  - E_T^{miss} > 45 GeV
  - Veto on additional muon with E_T > 20 GeV

  m_T (l, E_T^{miss}) requirement of [597, 796, 843] GeV

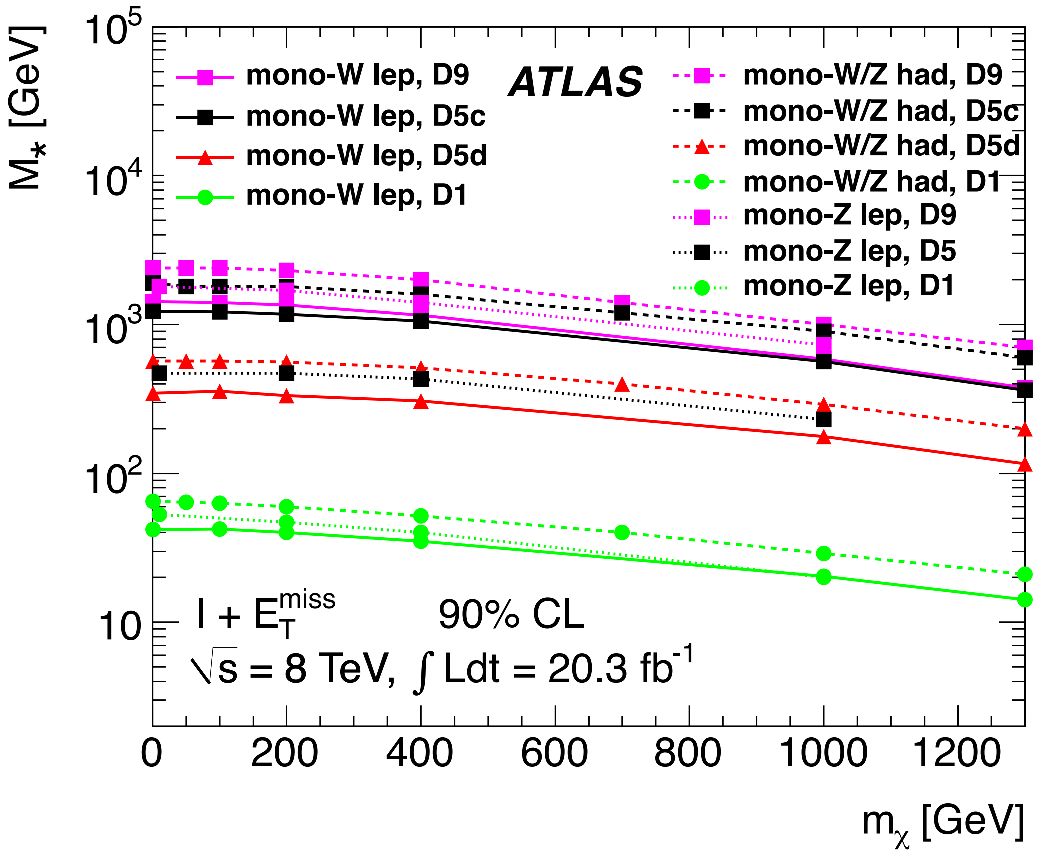
Shown for m_T > 252 GeV





Result

- Better constraint by mono-W/Z (hadronic decay) search



D5c: constructive interference

C(u) = -C(d)

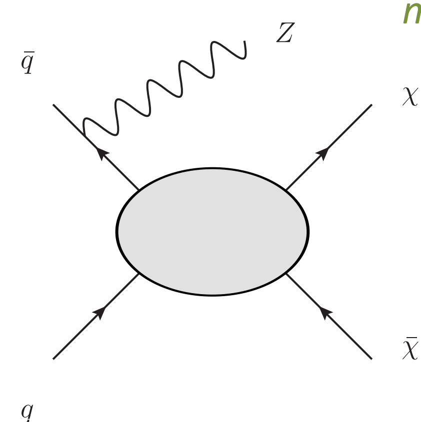
D5d: destructive interference

C(u) = C(d)

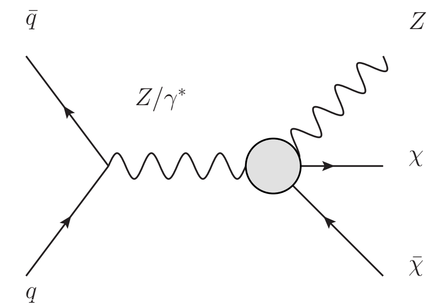
- **Mono-γ search**
- **Mono-jet search**
- **Mono-W/Z (hadronic) search**
- **Mono-W search**
- **Mono-Z search**

Mono-Z analysis

$\sqrt{s}$=8 TeV, 20 fb^{-1}
PRD 90 012004 (2014)



ISR
nucleon-χ

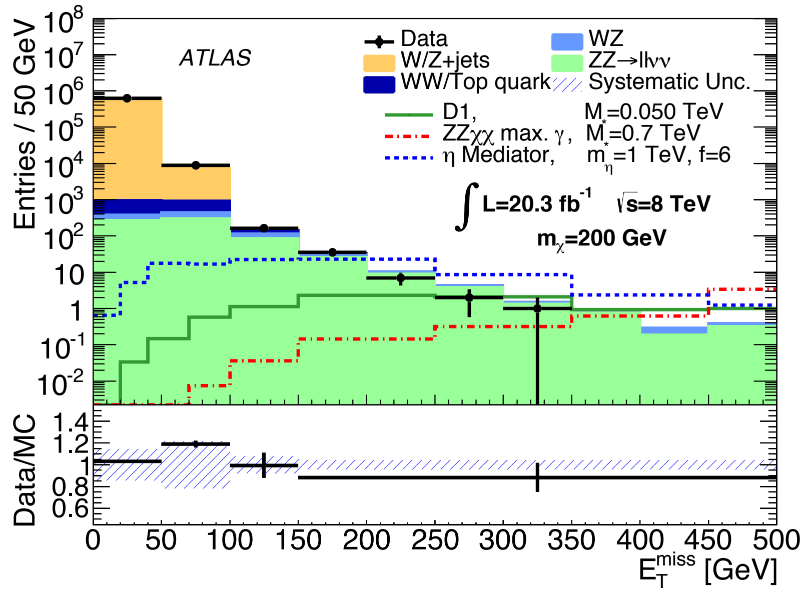


direct
Z-χ

- Search with leptonically decaying Z
  - Also sensitive to direct Z-χ interaction.
    - dimension-5 and -7 operators (PRD 87, 074005)
- Event selection
  - A opposite-sign lepton pair (e^+e^- or $\mu^+\mu^-$) with
    - leptons: p_T>20 GeV, $|\eta|$<~2.5
    - 76 GeV < m_{ll} < 106 GeV (Z mass peak), $|\eta_{ll}|$<2.5
    - well balanced against E_T^{miss}
  - Veto on 3rd leptons with p_T > 7 GeV
  - Veto on jets with p_T > 25 GeV, $|\eta|$<2.5
  - E_T^{miss} requirements
    - 4 signal regions: E_T^{miss} > 150, 250, 350 and 450 GeV

Event yields

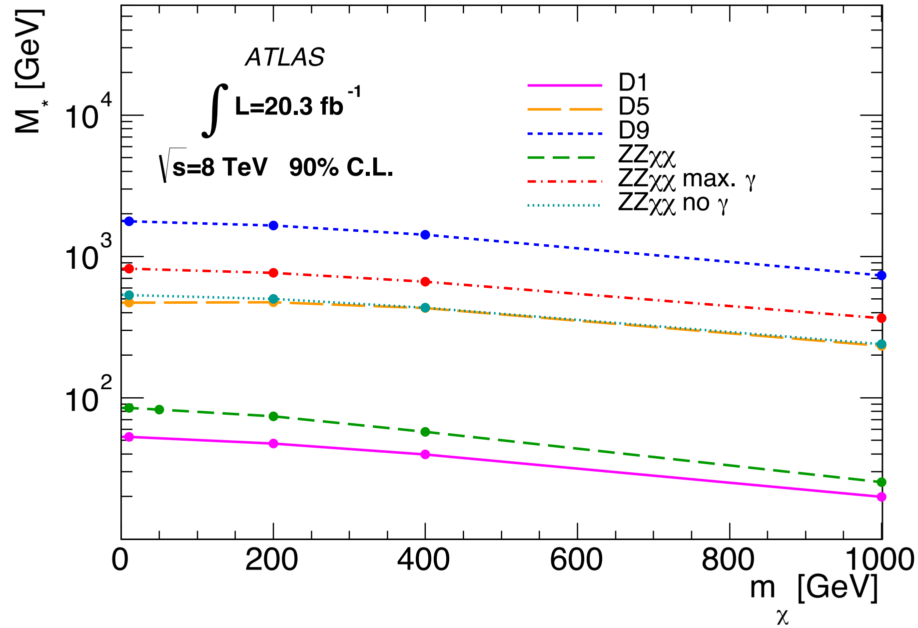
- Main backgrounds
  - ZZ and WZ, estimated using NLO MCs.
- No excess is seen

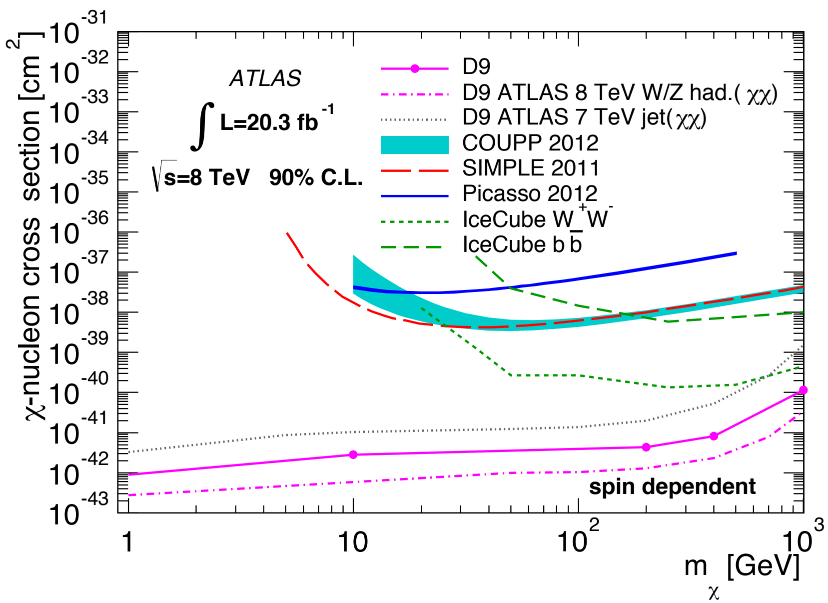


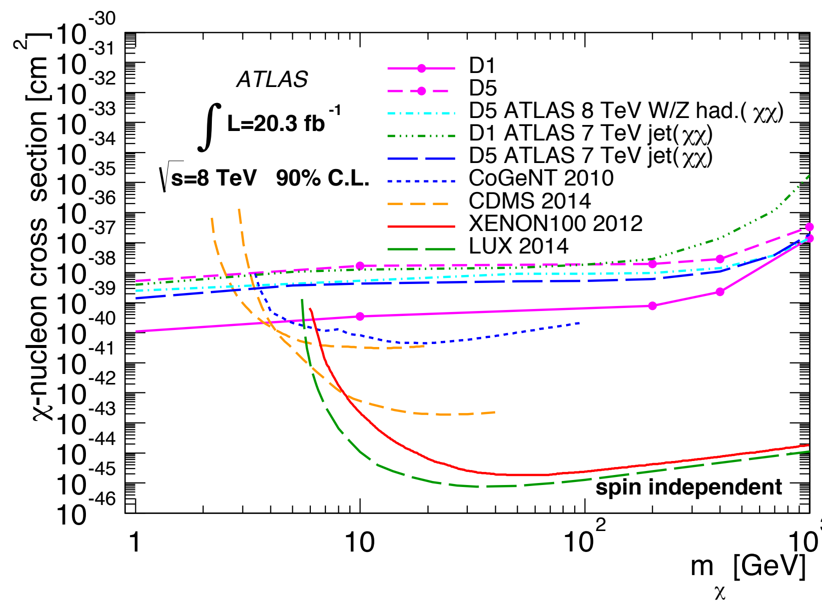
Process	E_T^{miss} threshold [GeV]			
	150	250	350	450
ZZ	41 ± 15	6.4 ± 2.4	1.3 ± 0.5	0.3 ± 0.1
WZ	8.0 ± 3.1	0.8 ± 0.4	0.2 ± 0.1	0.1 ± 0.1
WW, $t\bar{t}$, $Z \to \tau^+\tau^-$	1.9 ± 1.4	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$
$Z +$ jets	0.1 ± 0.1	...	...	...
$W +$ jets	0.5 ± 0.3	...	...	...
Total	52 ± 18	7.2 ± 2.8	1.4 ± 0.9	$0.4^{+0.7}_{-0.4}$
Data	45	3	0	0

EFT interpretation

- Nucleon-χ: D1, D5 and D9
- Z-χ:
  - dimension-5: ZZχχ
  - dimension-7: ZZχχ with maximum / negligible Zγ* contribution

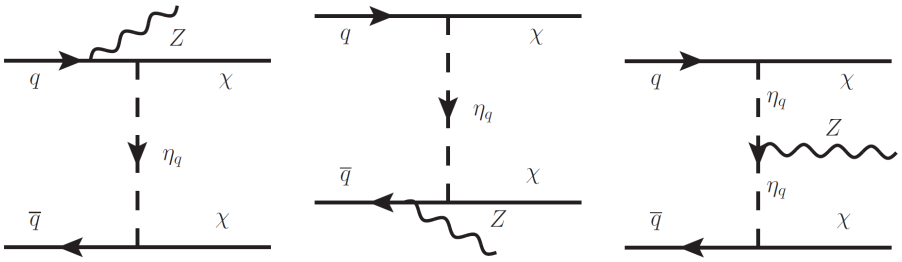


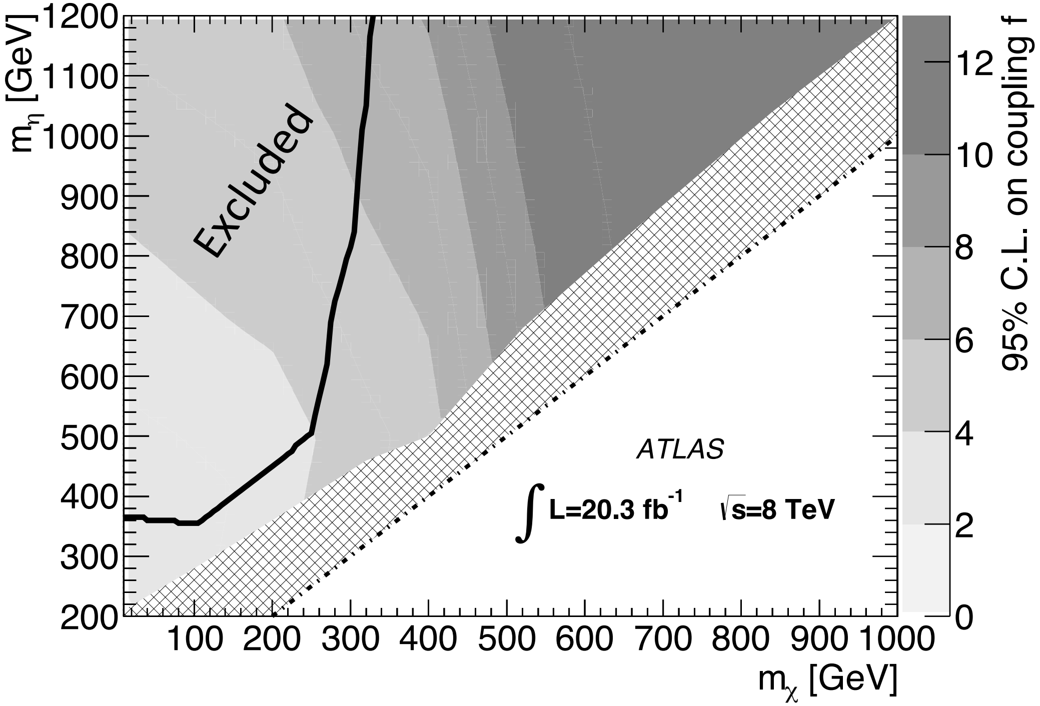




Interpretation with simplified model

- Assume scalar t-channel mediator *η*, with *η*-*χ* coupling strength *f*.
  - Color triplet, EW doublet, Y^W=1/3

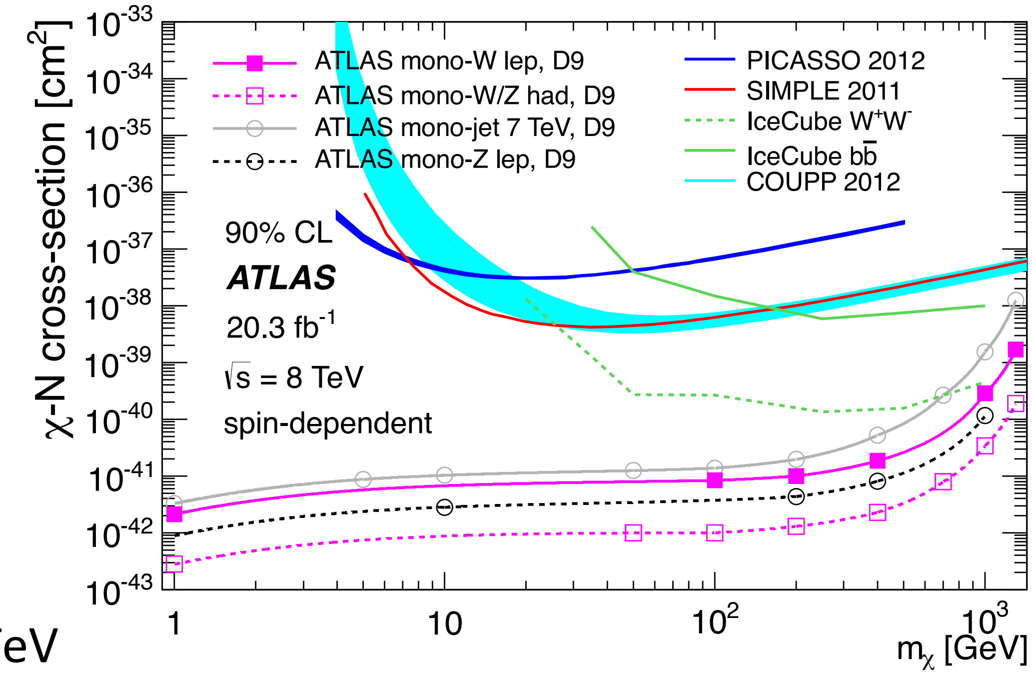


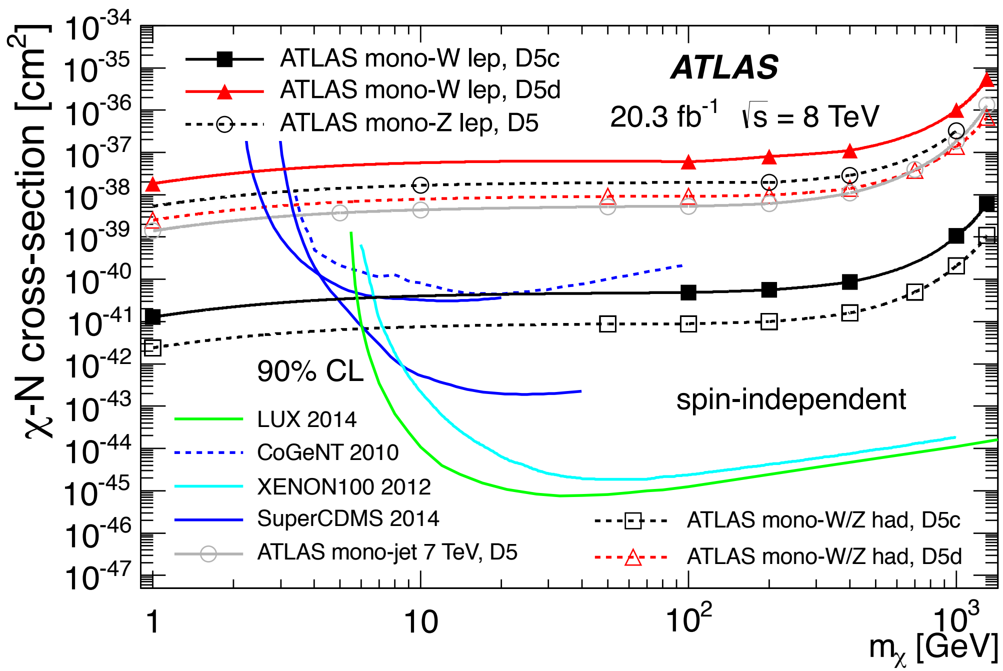


Summary:

Latest ATLAS Results

- Mono-jet @ 7 TeV
- Mono-W/Z (hadronic) @ 8 TeV
- Mono-W @ 8 TeV
- Mono-Z @ 8 TeV





Summary

- If Dark Matter couples Standard Model particles, DM can be produced at colliders.
- Search of WIMP pair production, with initial state radiation of energetic object:
  - Mono-X + large E_T^{miss}
- ATLAS has performed several Mono-X searches.
  - 7 TeV data (5 fb^{-1}) : X= photon, jet
  - 8 TeV data (20 fb^{-1}) : X= W/Z(->qq), W(->lv), Z(->ll)
- Good agreement is seen between data and SM predictions.
  - Limits are set on Effective Field Theory
- The coming 13/14 TeV runs are expected to give better sensitivity in DM searches.

Backup

EFT operators

from J. Goodman et. al., PRD 82, 116010 (2010)

TABLE I. Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars, respectively.

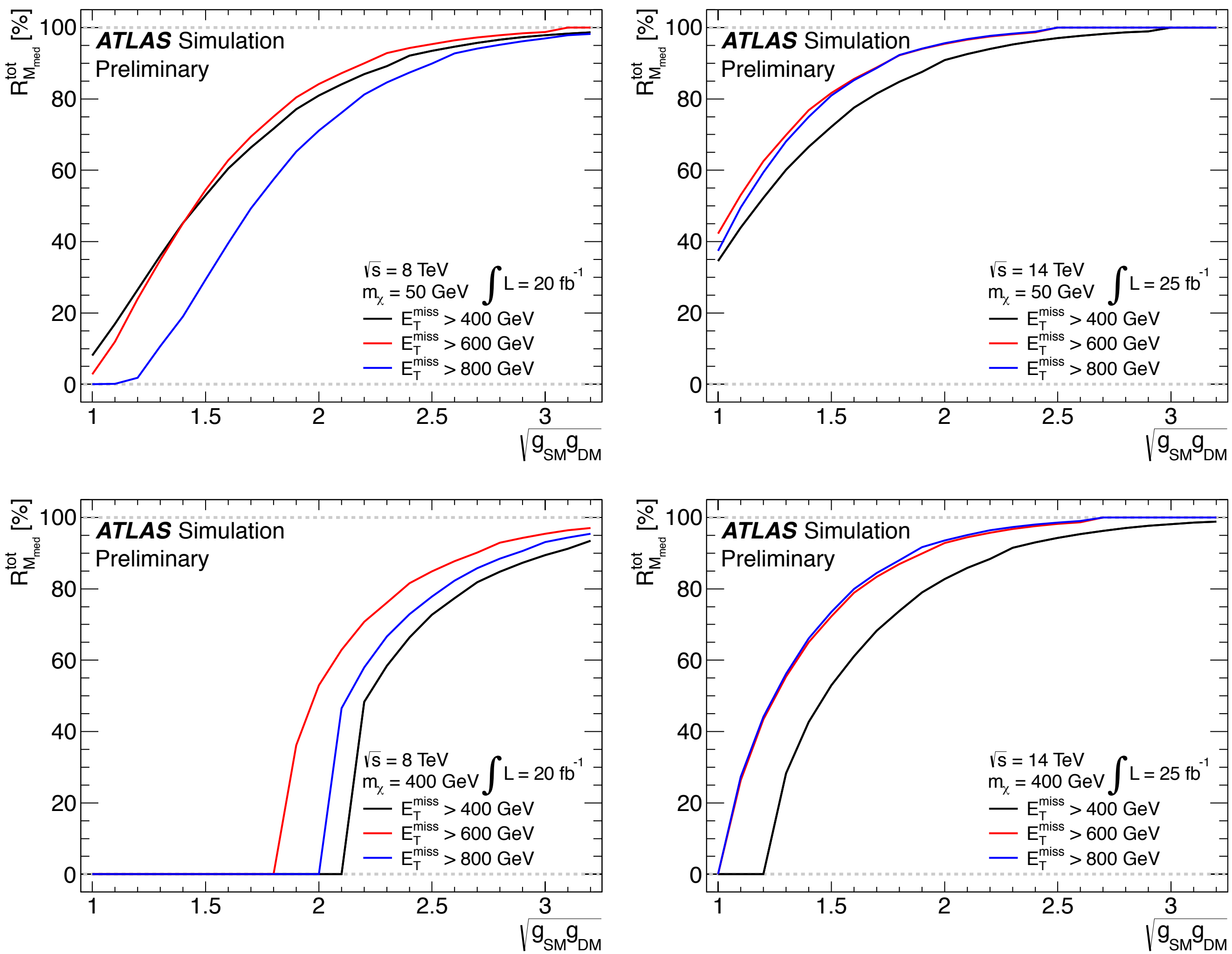
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Upgrade study: EFT validity

- Validity of EFT requires $Q_{Tr} < M_* \sqrt{(g_{SM} g_{DM})}$
  Q_{Tr}: interaction scale

R^{tot}_{Mmed}

Fraction of valid events



8 TeV mono-jet event yields

Background Predictions ± (stat.data)± (stat.MC) ± (syst.)				
	SR1	SR2	SR3	SR4
$Z(\to \nu\bar{\nu})$+jets	173600 ± 500 ± 1300 ± 5500	15600 ± 200 ± 300 ± 500	1520 ± 50 ± 90 ± 60	270 ± 30 ± 40 ± 20
$W \to \tau\nu$+jets	87400 ± 300 ± 800 ± 3700	5580 ± 60 ± 190 ± 300	370 ± 10 ± 40 ± 30	39 ± 4 ± 11 ± 2
$W \to e\nu$+jets	36700 ± 200 ± 500 ± 1500	1880 ± 30 ± 100 ± 100	112 ± 5 ± 18 ± 9	16 ± 2 ± 6 ± 2
$W \to \mu\nu$+jets	34200 ± 100 ± 400 ± 1600	2050 ± 20 ± 100 ± 130	158 ± 5 ± 21 ± 14	42 ± 4 ± 13 ± 8
$Z \to \tau\tau$+jets	1263 ± 7 ± 44 ± 92	54 ± 1 ± 9 ± 5	1.3 ± 0.1 ± 1.3 ± 0.2	1.4 ± 0.2 ± 1.5 ± 0.2
$Z/\gamma^{*}(\to \mu^{+}\mu^{-})$+jets	783 ± 2 ± 35 ± 53	26 ± 0 ± 6 ± 1	2.7 ± 0.1 ± 1.9 ± 0.3	–
$Z/\gamma^{*}(\to e^{+}e^{-})$+jets	–	–	–	–
Multijet	6400 ± 90 ± 5500	200 ± 20 ± 200	–	–
$t\bar{t}$ + single t	2660 ± 60 ± 530	120 ± 10 ± 20	7 ± 3 ± 1	1.2 ± 1.2 ± 0.2
Dibosons	815 ± 9 ± 163	83 ± 3 ± 17	14 ± 1 ± 3	3 ± 1 ± 1
Non-collision background	640 ± 40 ± 60	22 ± 7 ± 2	–	–
Total background	344400 ± 900 ± 2200 ± 12600	25600 ± 240 ± 500 ± 900	2180 ± 70 ± 120 ± 100	380 ± 30 ± 60 ± 30
Data	350932	25515	2353	268

Table 2: Number of observed events and predicted background events, including statistical and systematic uncertainties. The statistical uncertainties for data and MC simulation are shown separately. In the total background prediction the first quoted uncertainty reflects the contribution from the statistical uncertainty in the data in the control regions affecting the electroweak background estimation, the second represents the MC statistical uncertainty, and the third includes the rest of systematic uncertainties. In SR3 and SR4 selections the MC statistical uncertainty dominates. The background uncertainties in SR1 and SR2 selections are dominated by the rest of systematic uncertainties.